3.15 The Respiratory System

Figure 1
Scuba technology allows our respiratory system to continue to function properly when we are under water for long periods of time.

The intimate link between humans and their environment is clearly demonstrated every minute of every day. Humans, while very adaptable (**Figure 1**), can survive for only a few minutes without oxygen.

All animals exchange gases with their surroundings. Animals take in oxygen gas and release carbon dioxide in the process of **respiration**. The oxygen reacts with nutrients in mitochondria to release energy. Carbon dioxide is a waste product produced by these same reactions. Unlike water and food, gases cannot be stored easily within living tissues, and, therefore, most animals must exchange gases with the atmosphere on a continual basis.

TRY THIS activity — Fitness Test ($VO_{2\,max}$)

One way to measure your level of fitness is to calculate the maximum amount of oxygen that your body can use when you perform a very strenuous activity such as running. In theory, the greater your level of fitness, the greater the quantity of oxygen you can consume in a set time interval. $VO_{2\,max}$ is an estimate of the maximum amount of oxygen (in millilitres) that a person can use in one minute per kilogram of weight while breathing air at sea level.

Do not perform this activity if you are not allowed to participate in physical education classes.

This can be calculated using the following formula:

$$VO_{2\,max} = (\text{speed} \times 0.172) + 10.4$$

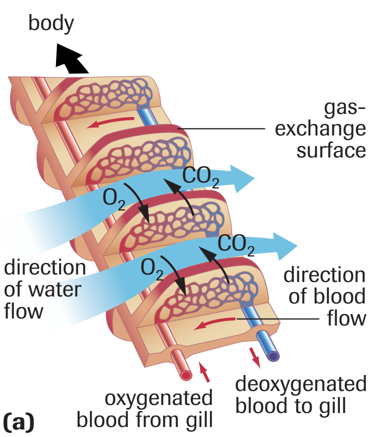
$VO_{2\,max}$ is expressed in mL/kg/min. Speed units are metres per minute (m/min).

Example: A student runs a distance of 400 m in a time of 1 min 20 s. Calculate the $VO_{2\,max}$.

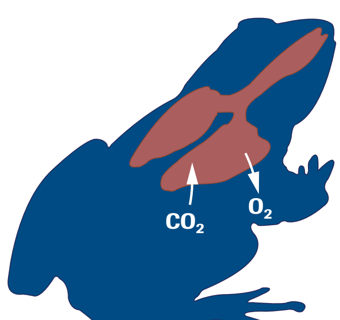
$$\text{Speed} = 400\text{ m}/1.33\text{ min}$$
$$= 301\text{ m/min}$$
$$VO_{2\,max} = (301 \times 0.172) + 10.4$$
$$= 62.2\text{ mL/kg/min}$$

A $VO_{2\,max}$ value over 35 mL/kg/min is considered good for females aged 13–19, while a $VO_{2\,max}$ value over 45 mL/kg/min is considered good for males aged 13–19.

(a) Determine your speed running a distance of at least 400 m. Apply the formula above to calculate your $VO_{2\,max}$.



(a)



(b)

Figure 2
Gas exchange in fish occurs at the gill surface **(a)**, while gas exchange in land animals usually involves a set of lungs **(b)**.

As you learned in section 3.9, a main function of the circulatory system is to transport oxygen and carbon dioxide to and from the cells of the body. Animals use large moist surfaces in order to exchange these gases between the blood and their external environment—the atmosphere or water. At these surfaces, gas exchange occurs by the process of diffusion. In aquatic animals,

such as fish, gas exchange occurs as water flows over large gill surfaces. In most land animals, this exchange occurs in lungs (**Figure 2**).

respiration all processes involved in the exchange of oxygen and carbon dioxide between cells and the environment

The Human Respiratory System

Humans are large warm-blooded animals called **endotherms**, with a very high oxygen demand. This demand is met using the structures of the human respiratory system illustrated in **Figure 3**.

endotherm an organism that maintains a near-constant body temperature. All birds and mammals are endotherms.

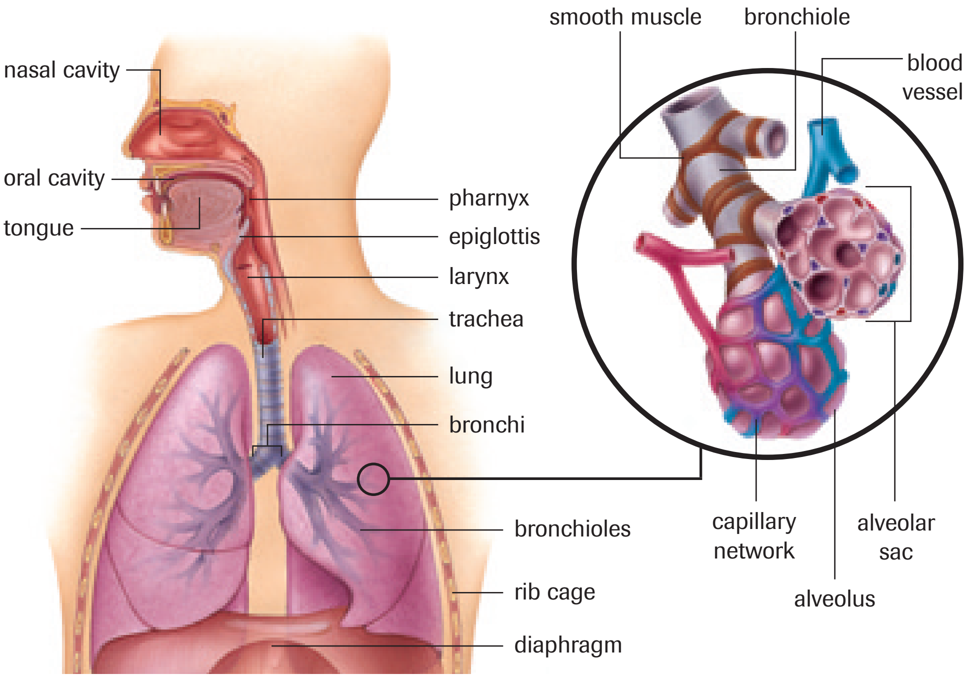


Figure 3
The human respiratory system

DID YOU KNOW?

Eat Carefully

Every year people choke to death on hotdogs because wieners have a shape ideally suited for getting stuck in the trachea.

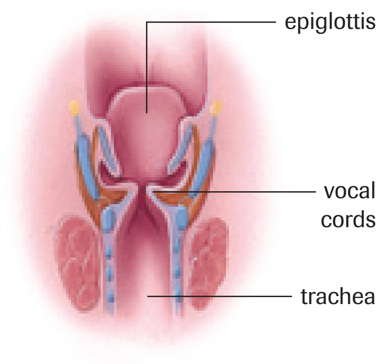


Figure 4
Larynx, showing vocal cords

Air usually enters the respiratory system through your nostrils. Dust and other foreign particles are trapped and filtered out of the air by tiny hairs and a layer of mucus that line these passages. The incoming air is also warmed and moistened by these surfaces.

At the back of the mouth, the nasal and oral cavities join to form a region called the pharynx. From the pharynx, air passes down through the **trachea**, or windpipe, into the lungs, while food enters the esophagus and is passed to the stomach. A very important flaplike structure called the **epiglottis** is located at the top of the trachea. When you swallow, a reflex causes the epiglottis to close over the opening of the trachea to prevent your food from accidentally entering the trachea. If you accidentally swallow too quickly or laugh, food or liquid may get past the epiglottis and enter the trachea. This usually results in another of your body's reflex actions—a cough.

The **larynx**, or voice box, is located in the trachea just below the epiglottis (**Figure 4**). The larynx contains two thin elastic ligaments, called vocal cords, that are under muscular control. When air is forced up from the lungs and through the larynx, the vocal cords vibrate, producing sounds. Different sounds are produced and controlled by adjusting the position and muscular tension of the vocal cords.

trachea the windpipe through which air passes from the pharynx toward the lungs

epiglottis the structure that covers the opening of the trachea during swallowing

larynx the enlarged portion of the trachea containing a pair of vocal cords

DID YOU KNOW?

Laryngitis

When you have laryngitis and "lose your voice," your vocal cords are inflamed (swollen) and unable to vibrate properly.

bronchus one of the air passages from the trachea that goes to the right or left lung

bronchiole one of the small air passages located within and throughout each lung

goblet cell a specialized cell that produces mucus

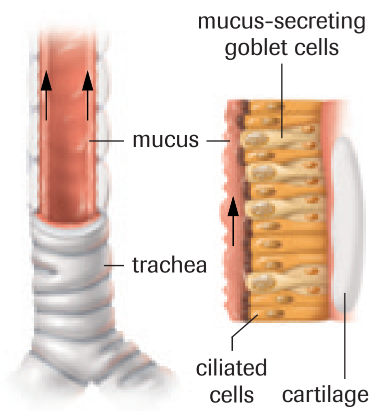


Figure 5
Goblet cells in the lining of air passageways produce mucus, which then traps debris and is carried up and out of the lungs by the action of cilia.

alveolus one of the tiny air sacs within the lungs in which gas exchange occurs between the air and the blood

In males, the larynx increases in size following puberty. The vocal cords vibrate at a lower frequency, producing a lower voice in men.

Inhaled air moves down through the trachea and into two **bronchi** (singular: bronchus). The trachea and bronchi are both surrounded and supported by many thin rings of cartilage that hold them open while remaining flexible.

Air enters the lungs through the bronchi that then divide into an extensive network of smaller tubes called **bronchioles**. Smooth muscles located in the walls of the bronchioles can contract to decrease the diameter of these small air passages. The inner linings of the trachea, bronchi, and bronchioles are covered by cilia and contain mucus-producing **goblet cells** (**Figure 5**). The mucus traps tiny particles such as bacteria, dust, and pollen that are then carried up out of the lungs and trachea by the sweeping action of the cilia. This continuous flow of mucus and trapped material is referred to as the bronchiole escalator.

Leading into the lungs, the branching bronchioles become smaller and smaller until they reach a dead end in the tiny air sacs called **alveoli** (singular: alveolus). It is in the alveoli that the actual exchange of gases between the air and the blood takes place. Each lung is made up of about 150 million alveoli, with each measuring between 0.1 mm and 0.2 mm in diameter. The total surface area of alveoli within a pair of lungs is approximately 80 m^2—about 40 times the surface area of your skin!

A network of capillaries surrounds each cluster of alveoli. Blood entering the network has a low oxygen concentration and a high carbon dioxide concentration. This blood passes through the capillary network, where oxygen gas diffuses from the air space within the alveoli through the single-celled walls of the alveoli and capillaries and into the blood (**Figure 6**). Simultaneously, carbon dioxide diffuses out of the blood and into the air of the lungs following the reverse path. Blood leaving the capillary network is now high in oxygen and low in carbon dioxide.

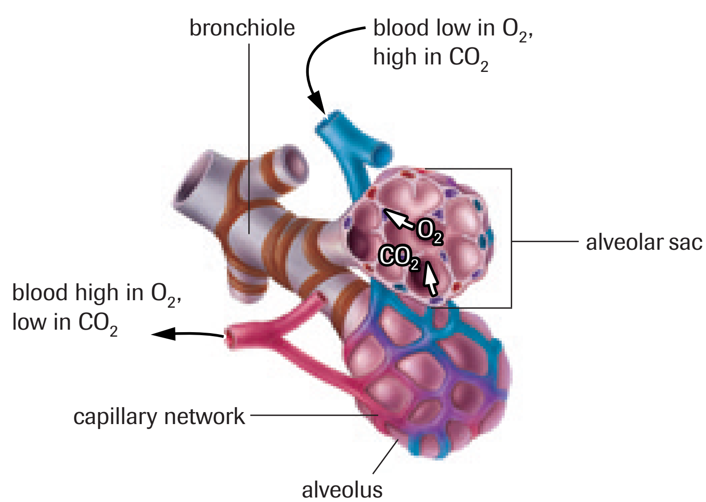


Figure 6
Gas exchange occurs between the air within the alveoli and the blood in the surrounding capillary network.

How We Breathe

Air within the alveoli must be exchanged regularly in order to provide a fresh supply of oxygen and to carry away waste carbon dioxide gas. This involves two main stages of breathing: **inspiration** (inhaling), in which air is moved into the lungs, and **expiration** (exhaling), in which air is forced out of the lungs.

Understanding how such air movement occurs requires an understanding of air pressure. Air will always move from an area of high pressure to an area of low pressure. Therefore, if the air pressure inside the lungs is less than the air pressure outside the body, air will move into the lungs. Similarly, if the air pressure inside the lungs is greater than the air pressure outside the body, air will leave the lungs. How does the body change the pressure within the lungs?

Carefully examine **Figures 7** and **8**. The lungs are located within the chest, or thoracic cavity. This large cavity is surrounded by the rib cage and a thin sheet of muscle called the **diaphragm**.

During inspiration, the diaphragm contracts and moves downward while the rib cage expands upward and outward by the actions of the **external intercostal muscles**. The result is an increase in the volume of the chest cavity. This lowers the air pressure inside the chest. Air then moves down through the trachea into the lungs, filling this extra space.

During expiration, the diaphragm relaxes and moves upward while the rib cage moves inward and downward. This decreases the volume and increases the air pressure within the chest cavity. This results in the movement of air out of the lungs.

inspiration the action of breathing in, or inhaling, air

expiration the action of breathing out, or exhaling, air

diaphragm a sheet of muscle that separates the organs of the chest cavity from those of the abdominal cavity

external intercostal muscles muscles between the ribs that raise the rib cage, increasing volume and reducing air pressure within the chest

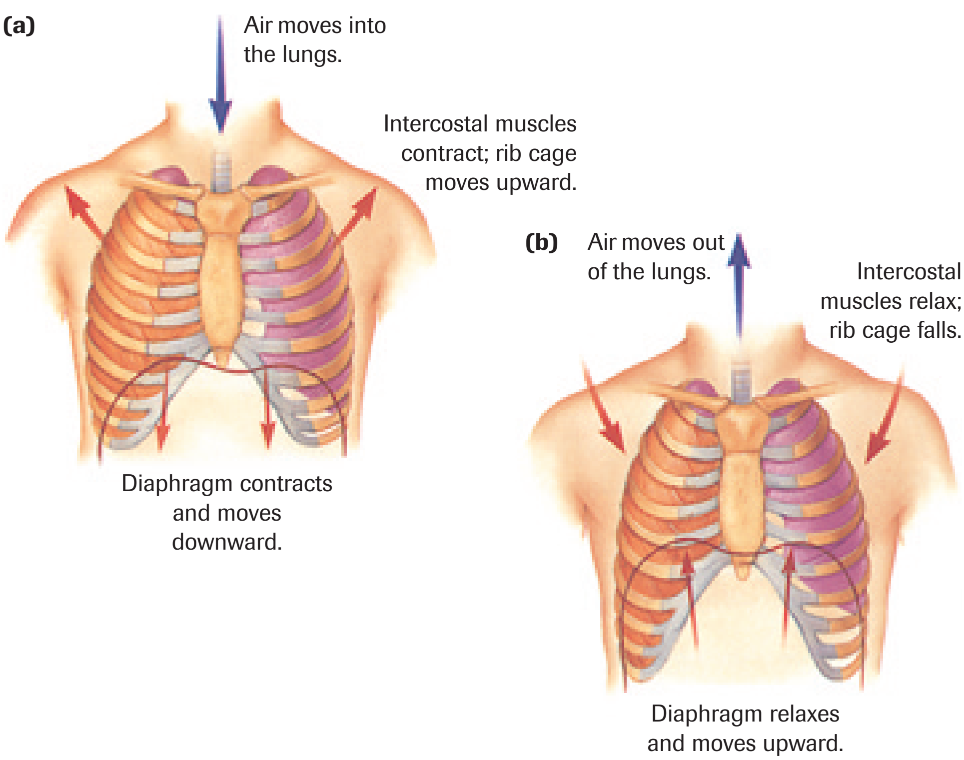


Figure 8
Changes in lung volume during **(a)** inspiration and **(b)** expiration

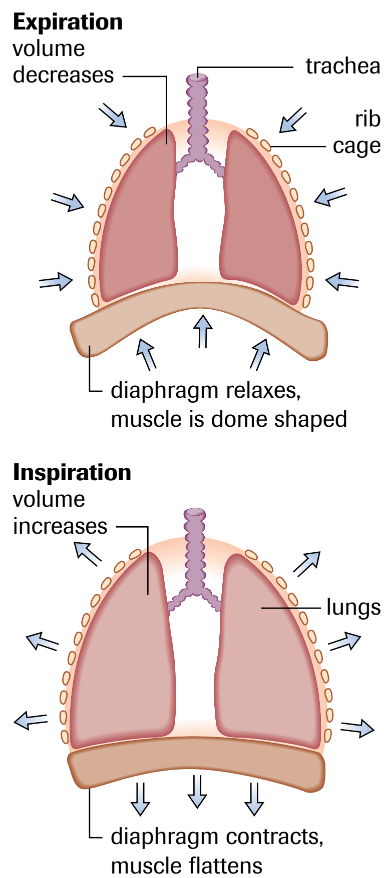


Figure 7
The lungs are contained within the chest, or thoracic cavity.

DID YOU KNOW?

Hiccups
Sometimes the diaphragm becomes irritated, causing it to experience muscle spasms. This forces air rapidly through the larynx, creating the sounds we call the "hiccups."

pleural membrane a thin, fluid-filled membrane that surrounds the outer surface of the lungs and lines the inner wall of the chest cavity

CAREER CONNECTION

Paramedics and other medical professionals are trained to seal openings in the chest wall resulting from serious injuries. They also assess and monitor breathing responses and take immediate action to maintain adequate gas exchange within the lungs.

Lungs continuously expand and contract. This constant motion could result in damage to their delicate outer surface. To prevent such damage, special **pleural membranes** cover the lungs and the inner walls of the chest cavity. A thin film of liquid between these membranes allows the lungs to move freely. These same membranes create an airtight seal around each lung. If this seal is punctured, air may be able to get in between a lung and the chest wall, causing the lung to collapse.

Maintaining fairly constant levels of oxygen in the blood depends on an alternating pattern of inspiration and expiration. This pattern is controlled by the autonomic nervous system, by nerve impulses from a breathing centre in your brain. Interestingly, the brain does not monitor oxygen levels in the blood, but instead monitors carbon dioxide levels. The greater the level of carbon dioxide in your blood, the faster your breathing rate will be. As you exercise vigorously, you consume oxygen quickly and produce a lot of carbon dioxide. Your brain detects this increase in blood carbon dioxide and increases your breathing rate.

Figure 10
Scuba divers use regulators and high-pressure tanks to ensure a safe air supply.

Breathing in Extremes

Humans often venture into environments with very unusual conditions (**Figure 9**). Scuba divers explore an underwater environment with much higher pressures than those found at the surface, while mountain climbers and others may live or spend time at very high altitudes where the air pressure is much lower than at sea level. These environments place extreme demands on the respiratory system.

At high altitudes there is less oxygen in the air, and our bodies compensate both by increasing our breathing rate and, over a period of days and weeks, by gradually increasing our number of red blood cells. At extreme altitudes, mountain climbers may have to carry oxygen tanks.

Scuba divers always carry their air supply in tanks and use special devices called regulators to compensate for the changes in pressure at different depths (**Figure 10**). Advanced and professional divers may use specialized mixtures of

DID YOU KNOW?

Nitrogen Narcosis

Scuba divers can suffer from a number of effects as a direct consequence of high pressures under water. Nitrogen narcosis is caused when too much nitrogen diffuses into the blood under high pressure. The symptoms may include mental impairment similar to the intoxication from alcohol consumption.

Figure 9
A thorough understanding of the respiratory system and the influence of pressure on gas exchange is essential for safe mountaineering and scuba diving.

gases, such as nitrox (32% oxygen and 68% nitrogen), for added safety and to extend their dive times. Pure oxygen is often deadly when breathed at depths below approximately 7 m and is not used in scuba tanks.

The Respiratory System of Frogs

The respiratory system of the frog changes dramatically during its life. Immature tadpoles live in the water and respire through a set of gills. When these tadpoles become adults, they leave the water and begin using a pair of internal lungs (**Figure 11**). Unlike humans and other mammals, frogs do not inhale by expanding their chest cavity. Instead, they must force air into their lungs by a gulping and swallowing action. Both immature and adult frogs also exchange gases directly through their moist outer skin (**Figure 12**).

Figure 12
Frogs are able to exchange gases directly through their moist living skin surface—something not possible through the dry skin surface of humans.

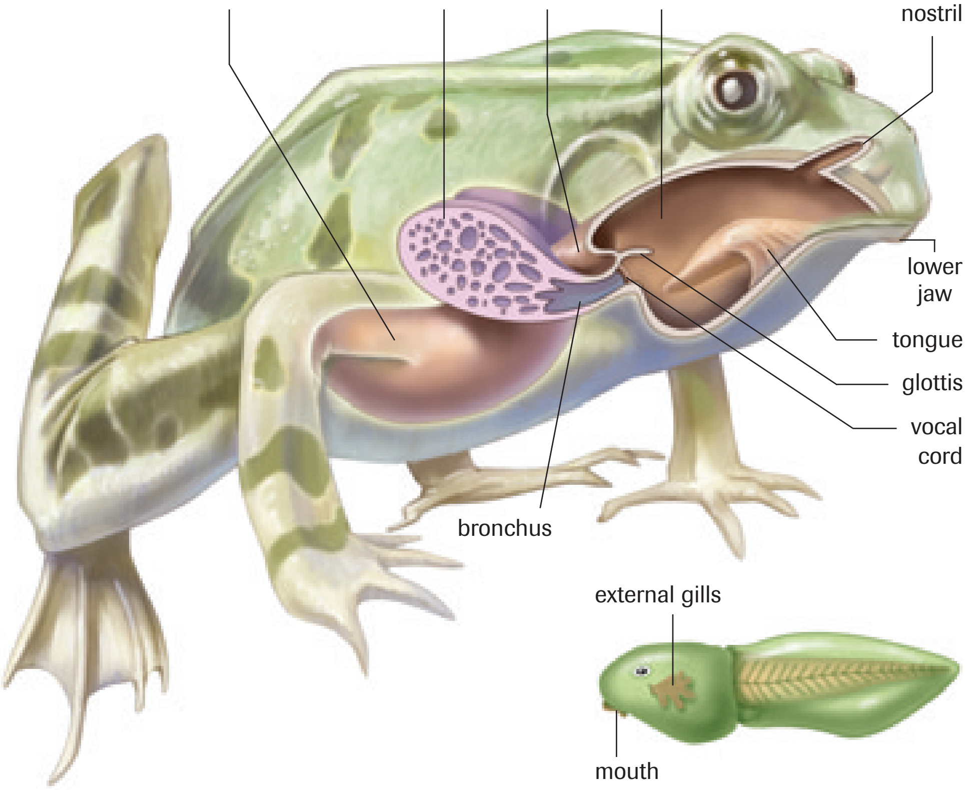


Figure 11
Tadpoles respire through their skin and external gills, while adult frogs breathe through their skin and a pair of simple internal lungs.

Section 3.15 Questions

Understanding Concepts

1. What are the main functions of the respiratory system?
2. How is the respiratory system related to the circulatory system?
3. Humans need to take in food and water only a few times each day. Why, then, is it necessary for us to breathe almost continuously?
4. State the main functions of the following:
   (a) epiglottis
   (b) trachea
   (c) cartilage rings of the trachea and bronchi
   (d) goblet cells
   (e) cilia
   (f) alveoli

5. Trace the path of an oxygen molecule in the air from the time it enters the body until the time it enters the bloodstream. Name each structure it passes or enters in the correct order.
6. Describe the structure and function of the larynx. How does the larynx differ in males and females?
7. Draw a fully labelled diagram of a functioning alveolus, illustrating blood flow and gas exchange.
8. Describe the muscle actions responsible for expiration and inspiration.
9. Briefly compare the respiratory system of the frog with that of the human. Consider the advantages and disadvantages of each.

Applying Inquiry Skills

10. Changes in the partial pressure of gases in arterial blood were monitored over time as a subject began to perform light exercise (**Figure 13**).

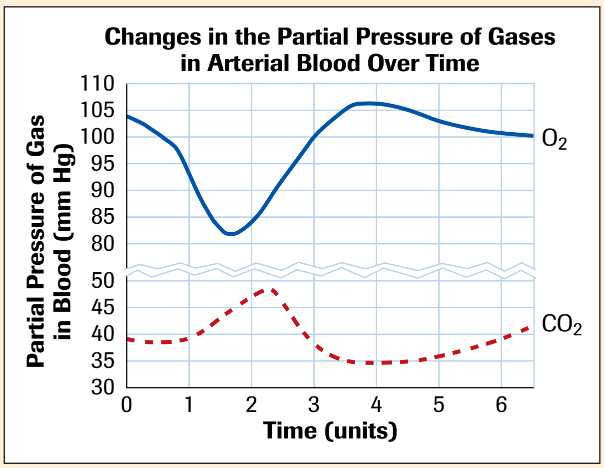


Figure 13

(a) At which time would the breathing rate likely be greatest? Provide reasons for your answer.
(b) Predict when the subject began exercising. Give your reasons.
(c) When would the breathing rate return to normal? Give your reasons.

11. A medical researcher suspects that people with cystic fibrosis (CF) have more respiratory infections than people who don't have CF because they produce thicker mucus in their lungs. In an investigation involving 1000 people over a period of one year, the researcher obtained the following results:

Number	Mucus viscosity + = normal ++ = thick +++ = very thick	Average frequency of respiratory infections (number per year)
750	+	2
235	++	3
15	+++	6

(a) Describe any evidence that supports the researcher's suspicion.
(b) Provide a hypothesis (a possible explanation) to explain how extra-thick mucus in the lungs could affect the frequency of respiratory infection.

Making Connections

12. A number of medical conditions, such as bronchitis, cause air passageways to narrow.
(a) What problems would be caused as the air passages decrease in diameter?
(b) What occupations or working environments are likely to aggravate bronchitis?
13. Research scuba diving and determine what sorts of courses are necessary to become a certified diver. Explore the career opportunities that may be available for professionally trained divers.

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Exploring

14. When someone is choking, an object is blocking his or her trachea. The Heimlich manoeuvre is often used to clear this obstruction. Research this first-aid action and be prepared to describe it to the class.

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